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WIND ENERGY VARIATIONS IN THE SOUTHWESTERN KALAHARI DESERT AND IMPLICATIONS FOR LINEAR DUNEFIELD ACTIVITY

J. E. BULLARD[1†], D. S. G. THOMAS[1*], I. LIVINGSTONE[2] AND G. F. S. WIGGS[1]

[1] *Sheffield Centre for International Drylands Research, Department of Geography, University of Sheffield, Sheffield S10 2TN, UK*
[2] *Department of Geography, Nene College, Moulton Park, Northampton NN2 7AL, UK*

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ABSTRACT

The southwestern Kalahari linear dunefield, which displays marked morphological variability, possesses a partial but temporally and spatially variable vegetation cover and has frequently been described as a palaeodunefield. Palaeo status has been ascribed on the basis of several criteria including the presence of vegetation, but also because dunes are thought to be out of alignment with modern resultant potential sand-moving wind directions and because present-day wind energy is regarded as low. For the period 1960–1992, wind data from eight dunefield meteorological stations are analysed in detail to examine these assertions. Potential sand transport directions, including spatial and temporal variations, and potential drift directions for the windiest three month periods, are calculated and explained. It is concluded that the present-day potential sand transport environment is markedly variable from year to year and from place to place. While periods of low sand transport energy do occur, it is also noted that the 1980s possessed considerable potential for sand transport in the dunefield. Directional variability is also relatively high, perhaps exceeding that under which linear dunes can be expected to form. Because linear dune aeolian activity has a number of states, however, the present-day wind environment may allow dune surface aeolian activity to occur which does not alter the overall pattern of the dunes.

KEY WORDS linear sand dunes; potential sand transport; potential sand drift directions; climatic variability; Kalahari

INTRODUCTION

Major advances in understanding desert sand dune development are being derived from detailed dune surface monitoring studies (e.g. Tsoar, 1978, 1985; Lancaster, 1985; Livingstone, 1986; Wiggs, 1992). Such studies are essential for explaining the interactions between factors such as the behaviour of the atmospheric boundary layer over dunes, sediment mobilization, transport and deposition at different positions on individual dunes, and dune morphological responses. These parameters have been and continue to be investigated on the principal dune morphological types (transverse/barchan, linear and star) and now on dunes that do not simply comprise bare sand surfaces. This is important because worldwide many desert dunes support various degrees of vegetation cover (Livingstone and Thomas, 1993), with sediment movement not totally excluded in the presence of plant cover (Ash and Wasson, 1993; Wiggs *et al.*, 1995, 1996).

Even with the growth of process studies on individual dunes, recognition has not been lost of the importance of more spatially extensive investigations of dunefield-wide conditions. Relationships between the regional wind environment and general dune form were first investigated comprehensively at the dunefield scale (Fryberger, 1979; Breed and Grow, 1979; Breed *et al.*, 1979) and methods developed in these studies

* To whom correspondence should be addressed.
† Current address: Department of Geography, University of Keele, Keele ST5 5BG, UK

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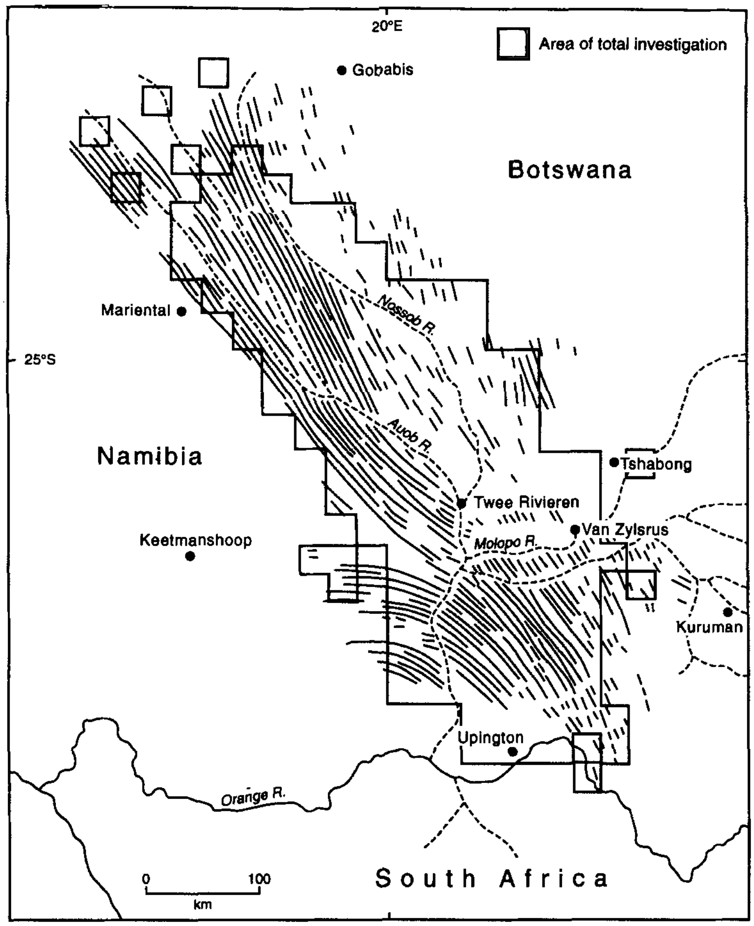


Figure 1. The southwest Kalahari, showing the dunefield and places referred to in the text

have been further utilized to examine possible regional-scale changes in wind regimes since the development of particular dunefields, especially those dominated by linear dunes (e.g. Lancaster, 1981; Thomas, 1984). Dunefield-wide investigations have also highlighted the genetic gradational relationships between different dune types in some dunefields (Lancaster, 1989; Lancaster *et al.*, 1987), which may relate to differences in the mobility and nature of activity of different types of dune (Thomas, 1992).

LINEAR DUNE STUDIES AT INDIVIDUAL DUNE AND DUNEFIELD SCALES

Linear dunes are one of the principal types of desert sand dune (Fryberger and Goudie, 1981; Thomas, 1989; Cooke *et al.*, 1993). Although individual, isolated forms can be found in some deserts (Tsoar, 1989), linear dunes are usually found in extensive dunefields (Figure 1). The term 'linear dune' embraces a variety of dune morphologies (Figures 2 and 3), which may form a continuum determined by the nature of surface activity (Livingstone and Thomas, 1993).

There are a number of climatic parameters that affect linear dune development and activity, of which wind regime and precipitation are arguably the most important. Wind regime directional characteristics may determine the nature and complexity of linear dune morphologies (e.g. Fryberger, 1979; Tseo, 1993) and regional wind patterns have also been examined in palaeoenvironmental studies. Based on Fryberger's

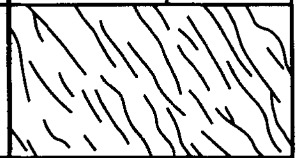
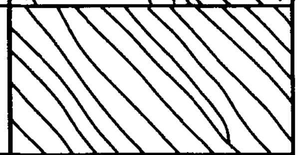
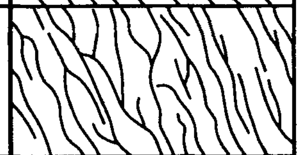
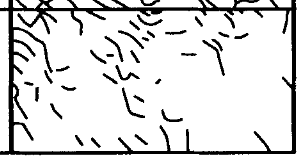
	General Description	Planimetric Pattern Example
1	Dunes parallel/sub-parallel, discontinuous occuring as short lengths (< 2km). Y-junctions uncommon and there are no transverse elements.	
2	Dunes parallel/sub-parallel and continuous for several km, few Y-junctions and no (or very rare) transverse elements. Those Y-junctions which do occur tend to form at the junction of two long dunes rather than as short spurs at the side of a dune. Occasional slip faces on crests but < $2m^2$.	
3	Dunes parallel/sub-parallel and continuous for several km. Y-junctions common,both as parallel dunes merge and as short spurs < 600m on either side of dune. No slip faces on undisturbed dunes but may be common where grazing occurs.	
4	Linear dune network comprising large steep dunes and smaller gently sloping dunes. Larger dunes have broadly linear trend but are very sinuous. Small dunes tend to be orientated perpendicular to this trend. Small pans occur in deep interdune areas. Both types of Y-junction occur, Y-junctions and terminii are common.	
5	No obvious linear trend and a chaotic hummocky appearance. Dune slopes shallow with very rounded crests. Dunes have low relief but occasional dunes up to 7 - 8m high. Very little interaction between dunes.	

Figure 2. Five-fold morphological classification of Kalahari dunes

(1979) suggestion that linear dunes form parallel to the resultant direction of modern-day sand drift (RDD, or resultant drift direction), deviations from this relationship for individual dunefields have led to inferences that circulation patterns have altered since dunefield development occurred (e.g. Lancaster, 1981). The second important aspect of the wind regime for dune development is wind energy which must exceed the threshold velocity for sand transport if dune surfaces are to be active. Wind energy is a key variable in indices designed to examine potential sand mobility such as that developed by Lancaster (1988) to consider past and present activity in the Kalahari dunefield.

Many dunefield-scale studies of linear dunes have treated precipitation as the control on dune activity. Put simply, these studies assume that rainfall leads to plant cover, which prevents sand transport by increasing dune surface roughness. This assumption was used to suggest that partially vegetated linear dunefields were currently inactive and therefore had a simple palaeoclimatic significance (e.g. Lancaster, 1981; Thomas, 1984). Theoretical arguments (Thomas and Shaw, 1991; Thomas, 1992; Livingstone and Thomas, 1992) have questioned the basis of this assumption, suggesting that surface vegetation on linear dunes may at least in part be due to the extending nature of linear dune activity, which does not necessarily incorporate mobility of the whole dune form. Thus the nature of linear dune activity may encourage vegetation colonization (Tsoar and Møller, 1986), rather than vegetation simply encouraging dune inactivity. Recent studies of aeolian processes and sediment movement on partially vegetated linear dunes in the Kalahari Desert by Wiggs *et al.* (1995; 1996) support the more general earlier findings of Ash and Wasson (1983) from Australia, namely that the presence of vegetation on linear dunes cannot be assumed to totally inhibit aeolian sediment transport.

The summary above indicates both the complex relationships between variables influencing surface activity on linear dunes and the value of both at-a-dune and regional dunefield studies for understanding

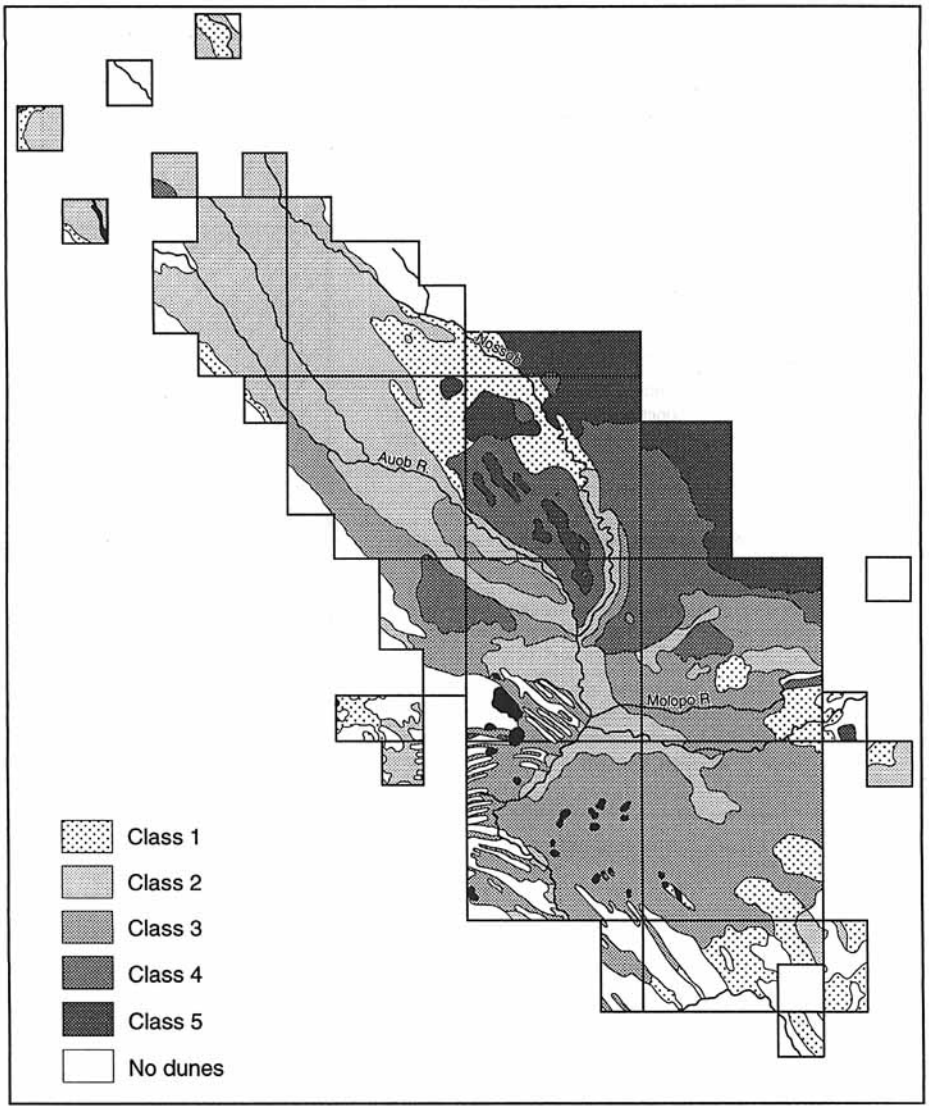


Figure 3. Duneform variation in the southwestern Kalahari (for classes see Figure 2)

dune behaviour. At-a-dune studies are essential for empirical process investigations, but dunefield-wide studies are necessary in attempts to translate our understanding to the most common scale and context of linear dune occurrence. However, dunefield-scale investigations need to be sufficiently detailed to take account of intra-dunefield variations in key parameters. In this paper, dunefield-scale variations in wind energy for sand transport are examined.

STUDY AREA AND AIMS: TEMPORAL VARIATIONS IN SAND TRANSPORT ENERGY

The southwestern Kalahari dunefield (Figure 1) has frequently been described as a palaeo-dunefield, based on suggestions that (1) available wind energy is too low for effective sand transport to take place (Breed *et al.* 1979; Lancaster, 1988); (2) the partial vegetation cover indicates inactivity (Lancaster, 1981; Thomas, 1984); and (3) circulation pattern shifts have occurred since dune development (Lancaster, 1981). The present mean

Table I. The energy of surface winds recalibrated for velocity data in m s^{-1} (modified from Fryberger, 1979)

Drift potential	Wind environment
> 27 vector units	low energy environment
27–54 vector units	intermediate energy environment
> 54 vector units	high energy environment

annual precipitation value of *c.* 200 mm across the dunefield has therefore been seen as too great to permit dune activity, while winds have been regarded as neither strong enough nor leading to the appropriate RDD for linear dune activity to occur.

This aim of this paper is to consider two of these criteria in detail by examining the nature and role of the wind energy environment in the southwest Kalahari in relation to potential dunefield-scale activity. The availability and analysis of wind data suitable for assessing wind energy and potential sand transport and transport direction is first considered. This is followed by an analysis of variations in the modern sand transport environment in the dunefield, and relationships with dune orientations in the vicinity of the recording stations. Finally, palaeoenvironmental implications of these data are considered.

DATA AND METHODS OF ANALYSIS

Breed *et al.* (1979) and Goudie and Thomas (1985) have analysed wind data from meteorological stations in the vicinity of the southwestern Kalahari linear dunefield in the context of investigating wind energy availability for sand transport and RDD. In both cases the widely cited 'Fryberger Method' of analysis (Fryberger, 1979) was utilized. This involves the application of frequencies of direction- and velocity-grouped data, for winds above a theoretically determined minimum velocity for sand transport, to a derivative of Lettau and Lettau's (1978) sand transport equation. This results in a simple vector output of the resultant direction of potential sand drift (RDD) expressed as the direction sand would be transported *towards*, DP (drift potential), a measure of available potential sand transporting energy, and the resultant drift potential (RDP) in the overall direction of transport. The last two values are presented as vector units (VU). In this study vector units are calculated using metres per second as the basic unit of velocity rather than knots as used by Fryberger (1979). This change in velocity units necessitates the recalibration of Fryberger's (1979) classification of wind energy environments (Table I).

The Fryberger Method makes a number of interpretative simplifications and assumptions that permit potential sand drift data to be calculated from simple wind velocity and strength measurements. In addition to these widely accepted limitations, the procedures introduced by Fryberger and adopted by other workers (e.g. Kalma *et al.*, 1988; Wal and MacManus, 1993) contain several weaknesses that necessitate careful handling of data and interpretations. These limitations and procedures to overcome them will be discussed elsewhere. Suffice it to note here that the Fryberger Method was adapted to account for these weaknesses.

Previous studies applying the Fryberger Method to this dunefield provided simple analyses from published mean wind data. However, the high inter-annual variability of dryland climatic parameters (Thomas and Middleton, 1994) has implications for the interpretation of 'non-time-bounded' mean values as demonstrated by Hulme (1992) for rainfall data. In this study temporal patterns of potential sand-moving winds are important for identifying variations and the possible episodicity of potential dune activity.

Wind data are collected at 0800, 1400 and 2000 from the eight stations. The wind speed is represented by the wind-run (the average wind velocity over the preceding six or 12 hours) whereas the wind direction is observed and the direction averaged over a few minutes at each time. There is therefore a difference between the time periods which the two readings represent; however, they represent the best data available for the region. Directional data were supplied for eight or 16 directions or in ten degree classes, depending on the station. Of more significance as a potential influence on results is the height of the anemometer above

Table II. Directional variability of winds (modified from Fryberger, 1979)

RDP/DP	Relative value of ratio	Directional variability of winds	Probability directional category
<0·3	low	high variability	complex/obtuse bimodal
0·3–0·8	intermediate	intermediate variability	obtuse bimodal/acute bimodal
>0·8	high	low variability	wide/narrow unimodal

the ground at each station, and its location relative to physical obstacles. Height information was collected either from the meteorological service concerned or by personal observations, and was calibrated to the WMO standard 10 m height assumed in the Fryberger Method. The anemometer at Twee Rivieren may yield anomalous results because it is located on a valley flank at a height of 4 m with several tall buildings nearby. This needs to be borne in mind when results are considered, as does the fact that the Van Zylsrus anemometer is located in a valley and not on the adjacent dune plateau.

For each year that data were available for each station, RDD, DP and RDP were calculated and sand flow roses produced (see Fryberger, 1979; Bullard, 1994). Other statistics, such as percentage of winds above the sand-transport threshold, adjusted to 5·97 m s^{-1} at 10 m height throughout the analyses, and the RDP/DP ratio, giving a measure of directional variability, were also computed.

RESULTS

A summary of results is presented below in the following categories: (1) summary data for the eight dunefield stations; (2) spatial and temporal variations in the potential sand transport environment; (3) seasonal variations in potential sand transport; (4) dune pattern and wind regime.

Potential sand transport direction and energy at the eight stations

At Gobabis, at the northern extremity of the dunefield, the RDD is consistently toward a southerly (180°) direction for all but one year in the analysis period 1966–1983 (Figure 4a). Fryberger (1979) used the ratio RDP/DP as a measure of direction variability (Table II). Directional variability at Gobabis is intermediate (Figure 4c) using this ratio, indicative of obtuse to acute bimodal wind regimes (Fryberger, 1979). Figure 4b also shows that at Gobabis potential sand-transporting winds represented no more than 10 per cent of all winds in any individual year, and rarely more than 6 per cent. DP reached a maximum in the early 1970s (Figure 4d), but was always in the low energy environment category of Fryberger (1979; Table I). The information in Figure 4e indicates the relative importance of winds in different velocity classes. The histograms indicate that a total of 91 per cent of DP is achieved by winds of 10 m s^{-1} or less.

Data for Mariental, on the western margin of the dunefield in Namibia, were sparse, only covering the years 1983–1985. During these years RDDs are 110°, 130° and 180°. DP values for two of the years indicate a high energy environment (values greater than 54 VU (m s^{-1})), but low energy in 1984. The availability of data for Keetmanshoop, to the south of Mariental on the western margin of the dunefield, is better, covering 1971–1985 (Figure 5). RDD varies from due south to due east, but in 1972 and 1981 was towards the north-east (Figure 5a). For most years over 10 per cent of all winds have the potential to transport sand, while directional variability (RDP/DP) varies from intermediate to high during the period of analysis (Figure 5c). Winds of 10 m s^{-1} or less account for most potential sand transport.

Twee Rivieren is located at the confluence of the Nossop and Aoub valleys and is the station located near the centre of the dunefield (Figure 1). Data for 1961–1992 (Figure 6) show a consistency in RDD at around 135°, but a dramatic increase in both DP and the percentage of potential sand-transporting winds for 1980–1990, when Twee Rivieren represents a high energy environment on the criteria of Fryberger (1979). Figure 6e also shows that high magnitude sand-moving winds are more common than at other stations, while RDP/DP values (Figure 6c) indicate that intermediate to high directional variability characterizes the Twee Rivieren potential sand transport environment.

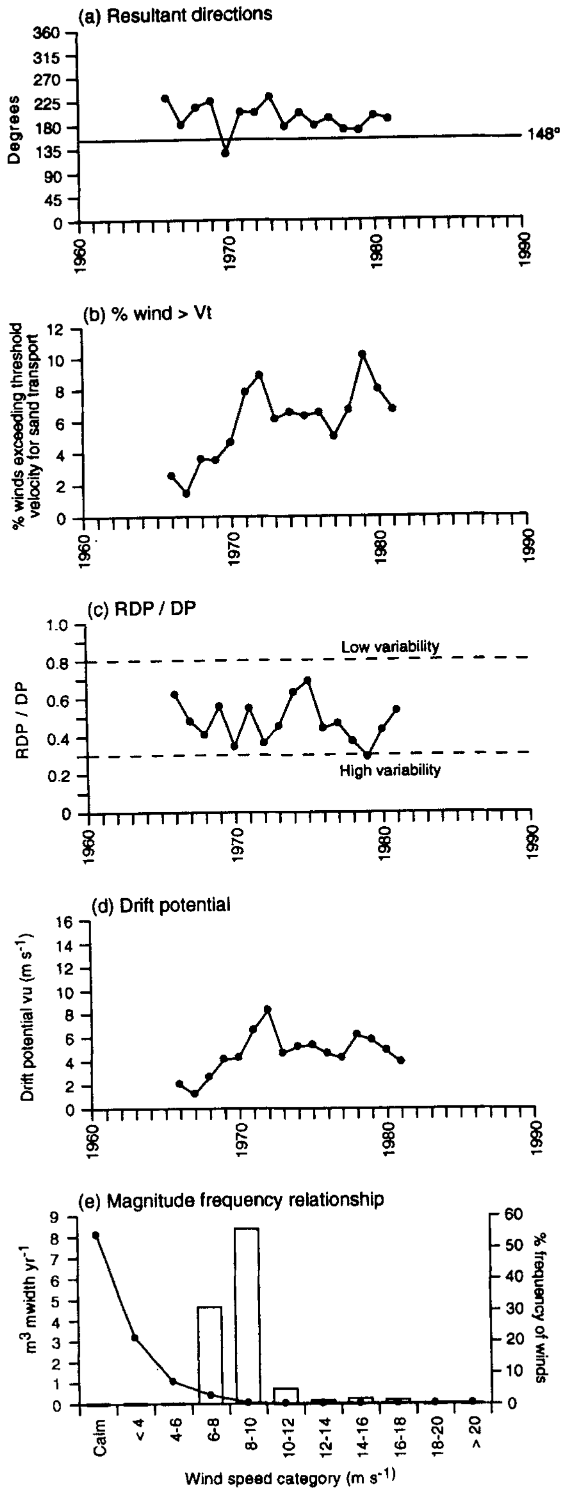


Figure 4. Potential sand drift characteristics at Gobabis

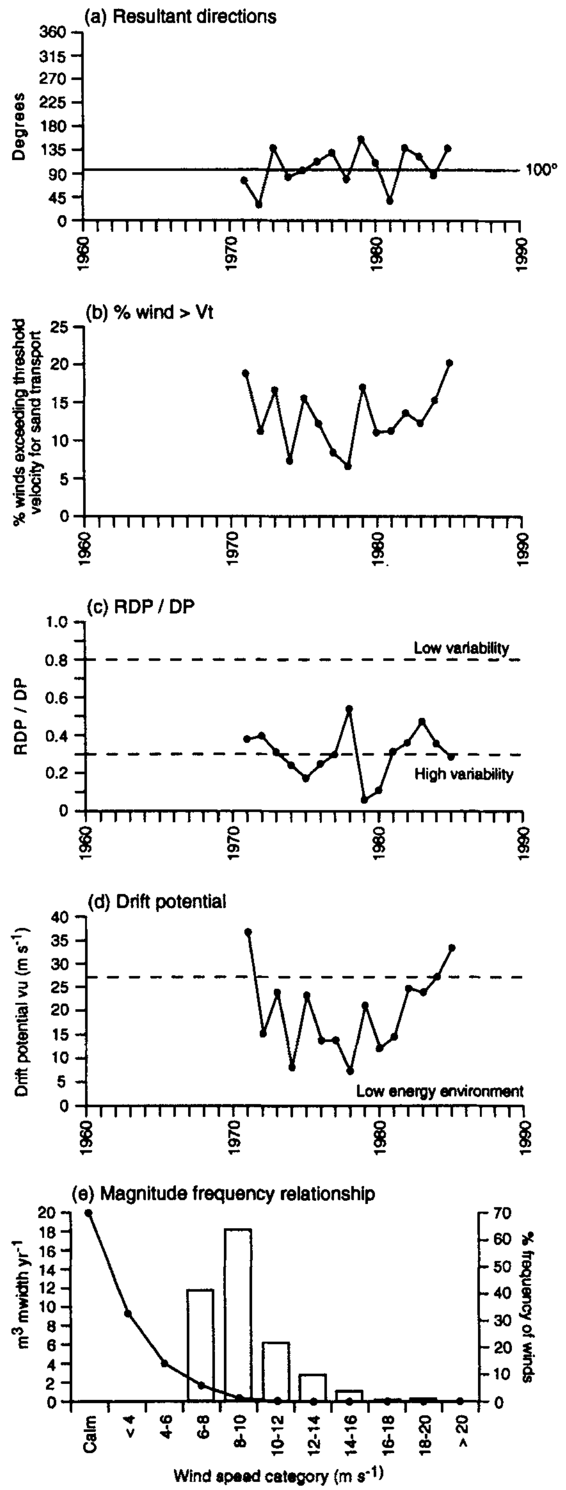


Figure 5. Potential sand drift characteristics at Keetmanshoop

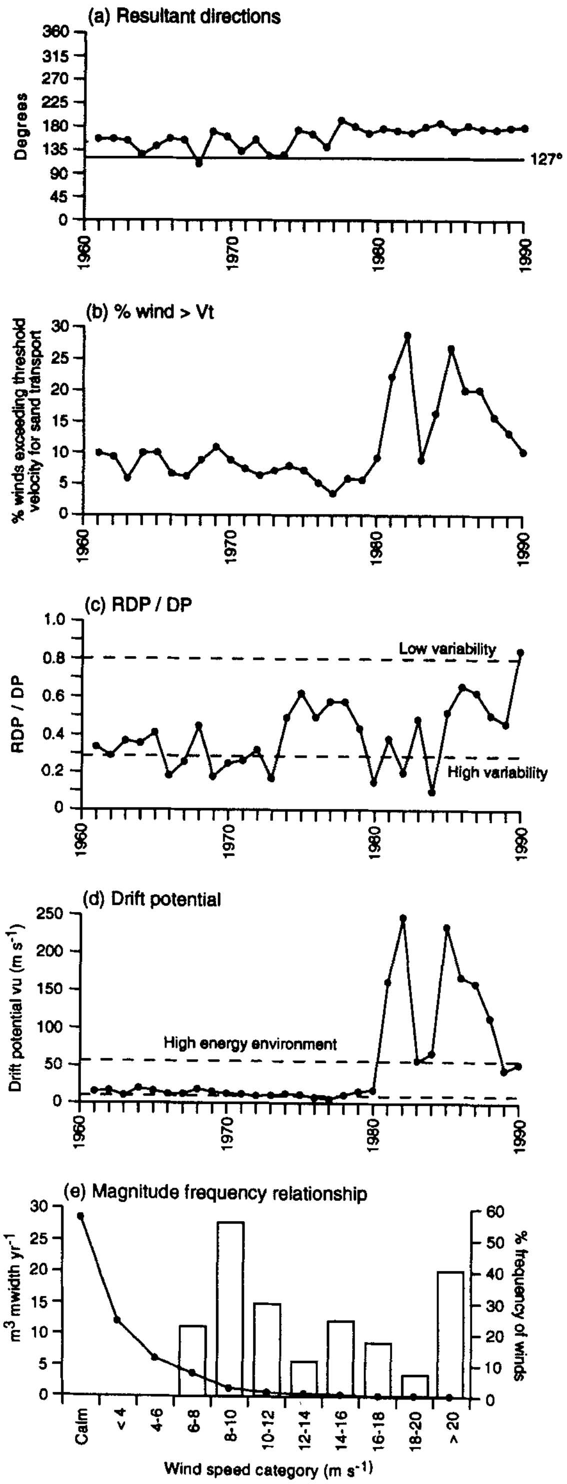


Figure 6. Potential sand drift characteristics at Twee Rivieren

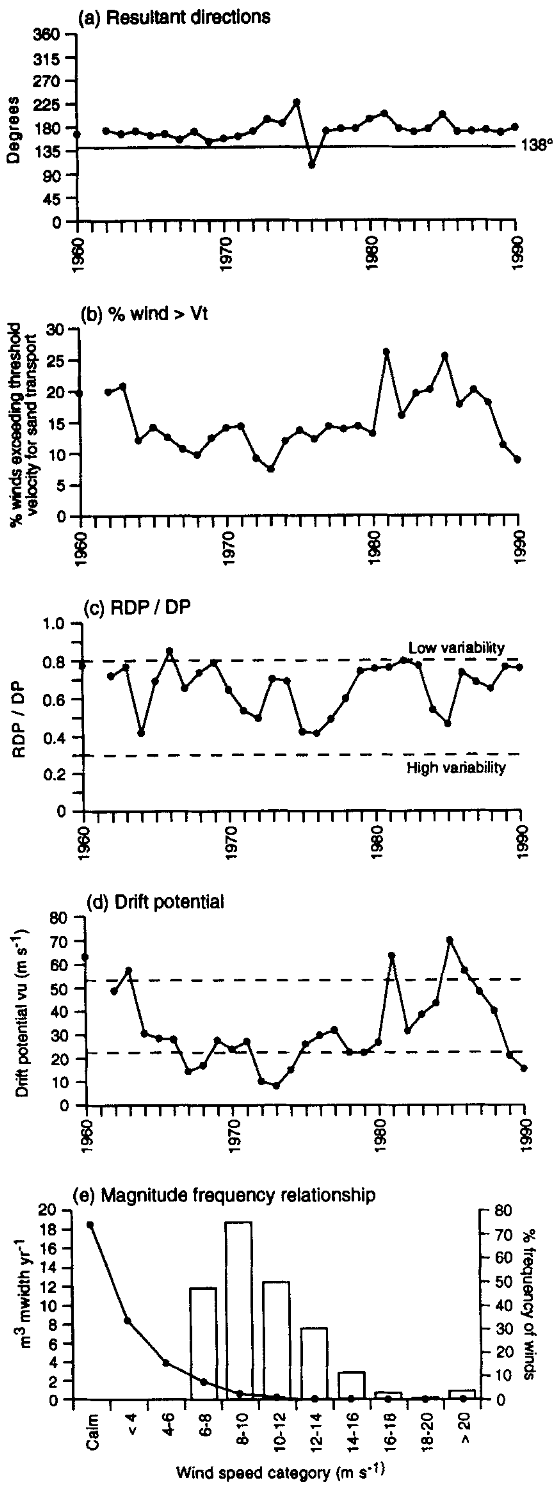


Figure 7. Potential sand drift characteristics at Upington

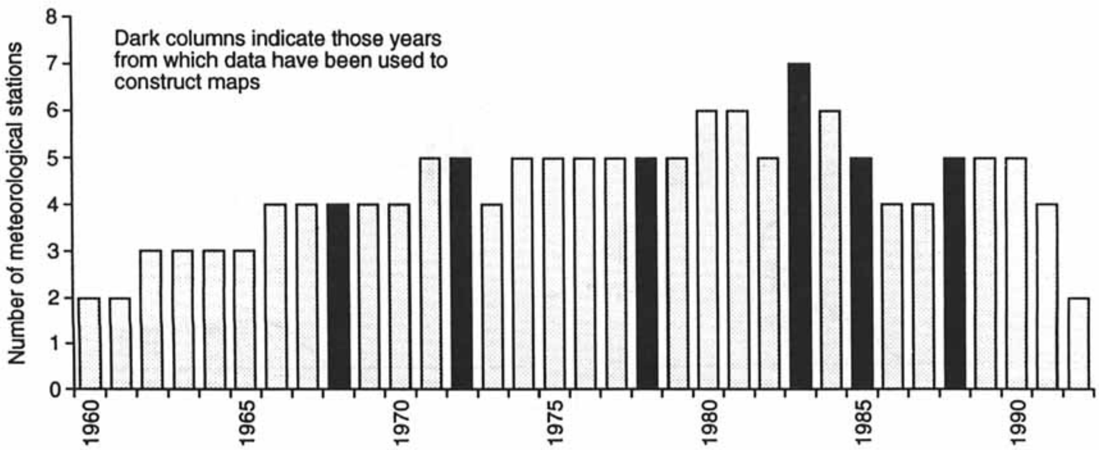


Figure 8. Meteorological data availability in the southwestern Kalahari, 1960–1992

Van Zylsrus and Tshabong represent conditions in the east margins of the dunefield. Van Zylsrus only has a 6 year data run (1985–1990) which possesses year-to-year directional variability in RDD ranging from 45° to 315°. DP is very low in all years except 1990 for which an extremely high DP of 67 VU is computed. Eleven years of wind data for Tshabong, commencing 1980, show RDDs in the 150–270° range and DP at a high energy environment maximum 108 VU in 1983, falling to intermediate and low values in subsequent years. There is similar year-to-year diversity in RDP/DP, from high (0·2) to low (0·8) values.

Two stations, Kuruman and Upington, are both located on the dunefield's southern margin. Although the Kuruman data commence in 1960 and span 31 years, major gaps occur precluding full analysis. Data for 1985–1987 are absent while oddly from 1970 to 1972 no winds whatsoever were recorded above the sand entrainment threshold. Outside these periods, RDD values are consistently in the 90–180° range except for one year, and DP values are indicative of a low energy environment apart from intermediate values in 1964, 1982 and 1991. Directional variability is principally intermediate. At Upington, where the airport at which meteorological data are recorded is flanked by linear dunes, a complete set of wind data is available for 1960–1992 (Figure 7). RDD is predominantly 180° but with individual annual oscillations from 90° to 225°. For individual years, percentage of sand-transporting winds range from 7 to 26 per cent, exceeding 10 per cent for all except four individual years (Figure 7b). DP values are mainly in the intermediate category but high and low energy environment conditions each occurred for three periods during the years under consideration (Figure 7d).

A notable trait in the above summaries is the interannual variability of RDD, RDP and DP both at individual stations and at different locations within the southwestern dunefield. Although it is not yet clear how short-term variations in wind energy may contribute to dune formation or modification, a knowledge of this variability is very important in terms of the interpretation of climatic data. Palaeoenvironmental interpretations of the southwest Kalahari based on data from a single year or unspecified mean values must be treated with extreme caution.

Spatial and temporal variations in the potential sand transport environment

Variability in station-to-station annual data availability (Figure 8) precludes a thorough systematic analysis of spatial trends in potential sand transport measures for each year. However, six years have been selected for consideration of spatial trends. These years have been chosen both to attempt to maximize the number of contributing stations, and thereby maximize spatial coverage, and to cover key periods in the variability in the time series for individual stations. The years selected are 1968, 1972, 1978, 1983, 1985 and 1988, with the number of contributory stations ranging from just four (1968) to seven (1983).

Figure 9 shows the annual potential sand-flow roses and DP and directional variability (RDP/DP) for each of the six years. In terms of the descriptive values of DP and RDP/DP of Fryberger (1979: Tables I and II), 1968, 1972 and 1978 were years of low energy (low DP) conditions throughout the dunefield (Figure 9).

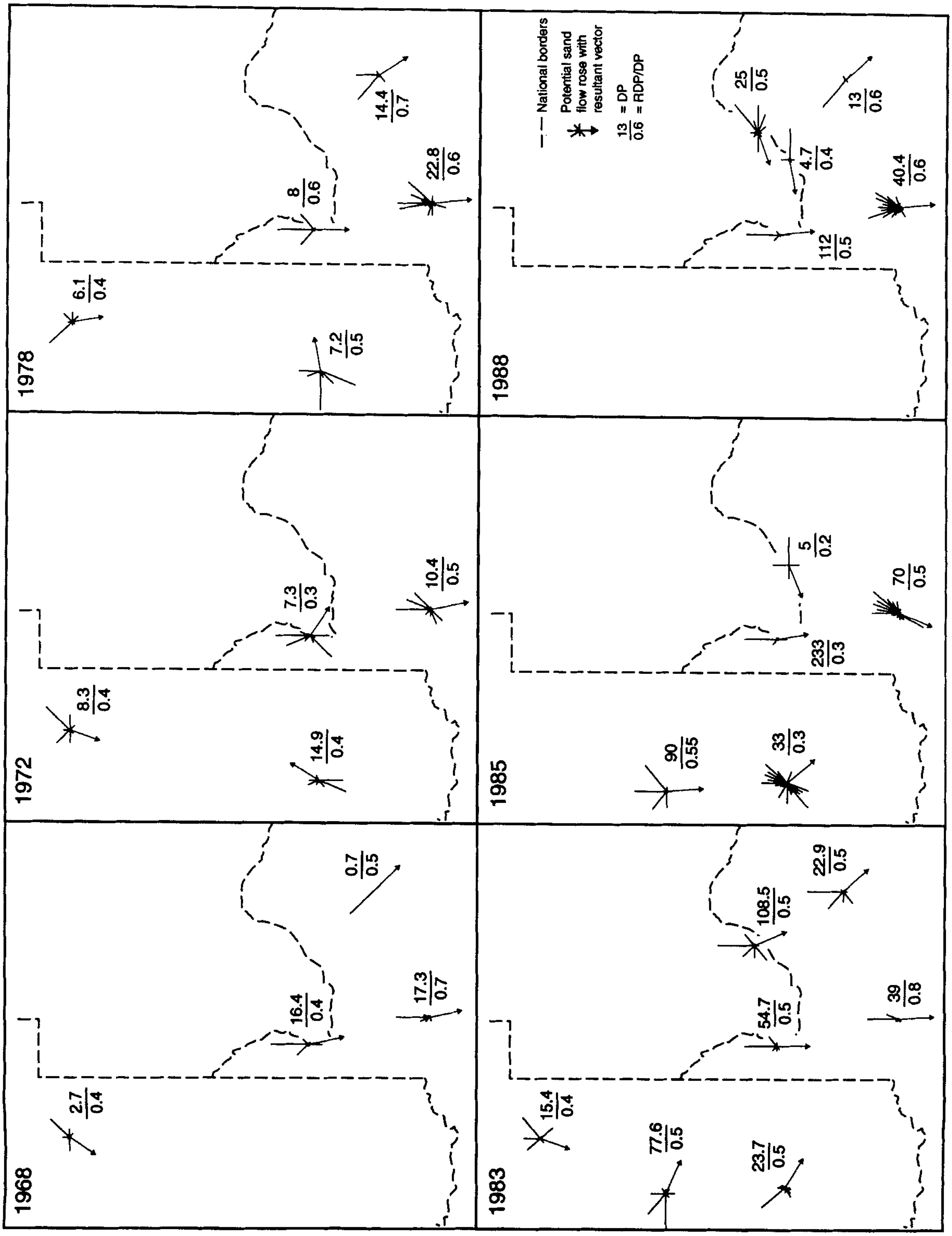


Figure 9. Spatial patterns in DP and directional variability (RDP/DP) for selected years

In all these years, energy is greatest in the south of the dunefield, at Upington. Potential sand transport directional variability (RDP/DP values, Figure 9) is intermediate (Tables I and II), comparable with Fryberger's (1979) observations of worldwide linear dune environments. During these three years, the RDD (shown by the resultant vector in the sand-flow roses in Figure 9) was toward the SW to SE in the north of the dunefield and S to SE in the south. The southerly trend in the centre of the dunefield was disrupted in 1972 when a SE vector occurred. An E to NE resultant vector dominates in the west of the dunefield.

The maps for 1983 and 1985 indicate that the early and mid-1980s was a period of enhanced potential sand transport (greater DP values) throughout the dunefield. Intermediate and even high energy environments existed in all areas except the northern and southern parts of the western dunefield margin in 1983. The high energy conditions persisted in 1985 in a belt running from the middle western margin areas, through the central dunefield, to southern areas. Data for 1988 only cover central-southern parts of the dunefield. They show that high and intermediate energy conditions persisting at Twee Rivieren and Upington, but low energy conditions in eastern areas.

With the exception of Upington in 1983, directional variability (RDP/DP values) is consistently intermediate throughout the dunefield during the years used to illustrate the 1980s conditions. It can also be noted that for any individual location, the resultant vector direction has a stronger southerly component when potential sand transport is greatest. The persistence of the southward potential drift direction is greatest in southern and central parts of the dunefield throughout the six years illustrated in Figure 9.

Seasonal variations in potential sand transport

While the year-by-year breakdown of the data illustrates the variability that can occur in the Kalahari dunefield potential sand transport environment, urging caution in the use of non-time-bounded mean values to characterize the wind energy environment, it is also possible to consider conditions on a month-by-month basis. Breed *et al.* (1979), Lancaster (1981) and Thomas and Shaw (1991) all proposed that the late winter (August–October) is the season of strongest winds, and therefore greatest potential sand transport, in the southwestern Kalahari. Further possible significance has been attached to this in an aeolian sediment movement context because this also coincides with the end of the dry season, when biomass is also likely to be low (Livingstone and Thomas, 1993).

Breed *et al.* (1979) suggested that the southwestern Kalahari windy season commenced earliest in the south of the dunefield and later in the north and east. The picture is in fact more complex than this (Table III). In the six individual years analysed for spatial and temporal trends in the potential sand transport environment (Figure 9), only in 1985 was August the month of greatest potential rate of sand transport at Upington in the south of the dunefield (Table III). In two of the six years (1978 and 1988), the windiest period commenced earliest at a location north of Upington, and in fact in 1978 the season of greatest winds seems to have

Table III. Timing of three month period of greatest potential sand drift in the dunefield. Letters in table refer to month initials

	Year					
Station	1968	1972	1978	1983	1985	1988
Gobabis	MJJ	OND	ASO	–	–	–
Mariental	–	–	–	JFM	SON	–
Keetmanshoop	–	JFM	OND	SON	ASO	–
Twee Rivieren	ASO	SON	OND	OND	ASO	SON
Tshabong	–	–	–	SON	–	JFM
Van Zylsrus	–	–	–	–	SON	–
Kuruman	ASO	SON	–	SON	–	OND
Upington	JJA	SON	JFM	ASO	ASO	OND

Note: In 1978 JFM for Upington refers to the end of the 1977–8 summer and at other stations months apply to beginning of 1978–9 summer.

Table IV. Mean dune orientation (from north) nearest to the eight meteorological stations, and the long-term mean RDD for three stations to the nearest semi-cardinal compass point

Station	Mean dune orientation	Long-term average RDD (time period)
Gobabis	148°	
Mariental	143°	
Keetmanshoop	100°	
Twee Rivieren	127°	South (32 yr average)
Tshabong	142°	
Van Zylsrus	160°	
Kuruman	127°	Southeast (29 year average)
Upington	138	South (30 year average)

progressed from a northerly direction (Table III). Table III shows that there is clear year-to-year variability in the onset of sand-transport conditions, with greatest consistency in the timing of the 'potential sand transport season' occurring in the centre of the dunefield (Twee Rivieren).

Dune patterns and wind regime

It is widely regarded, but by no means universally accepted, that linear dunes develop parallel or sub-parallel to the resultant direction of sand transport in bimodal wind regimes (Fryberger, 1979; Thomas, 1989, Cooke *et al.*, 1993), resulting in linear dunes being extending or sand passing dune forms (Thomas, 1992; Livingstone and Thomas, 1993) that do not necessarily experience full mobility of the dune body to be regarded as active dune forms. Using the terminology of Fryberger (1979: Tables I and II), the potential sand-flow roses shown in Figure 9 indicate that on a year-to-year basis conditions in the Kalahari dunefield usually generate obtuse bimodal or multimodal potential sand-flow regimes. These are compatible with the models of linear dune development and maintenance of Tsoar (1978) and Livingstone (1986).

General differences between dune orientation and the RDD of modern sand-transporting winds have been used to suggest that the Kalahari dunes were formed under different circulation conditions in the past (Lancaster, 1981). From the aerial photograph analysis conducted by Bullard *et al.* (1995), the mean orientation of 5 km lengths of 10 dunes nearest to each meteorological station has been calculated. The resulting values are shown in Table IV and are marked on Figures 4 to 7. In general the resultant drift directions calculated for each year are more southerly than the dune orientations, a relationship which was also noted for dunes in the northern Cape Province of South Africa by Le Roux (1990). He suggested that this may be due to a geostrophic wind effect, which may have little influence on sand movement because of the intermittent nature of particle movement. It is not possible to comment further on this without more detailed data. However, a further comparison can be made between dune orientation and the RDD during the three month periods of greatest potential sand drift (Table III). Figure 10 shows this comparison. For each year, the RDD has been calculated for the three month block with the greatest rate of potential sand transport. This has been done for stations representing each of the north, centre and south of the dunefield. It can be seen from Figure 10 that, apart from 1978 at Gobabis, there is little coincidence in mean dune orientation and RDD for these three month periods.

For the three meteorological stations with the longest records, Kuruman (29 years), Twee Rivieren (32 years) and Upington (30 years), long-term mean RDD was calculated. Although this calculation masks the annual variations in RDD it is indicative of the overall direction of sand transport over a length of time which may be more significant in terms of dune formation or modification. The long-term RDD for these three stations is given in Table IV. As in the case of the annual estimates, RDD is more southerly than the dune orientation, further supporting observations made by Le Roux (1990).

Figures 2 and 3 indicate that within the southwestern Kalahari dunefield, patterns of linear dunes are both complicated and spatially variable. While a more detailed analysis and explanation is provided by Bullard *et al.*

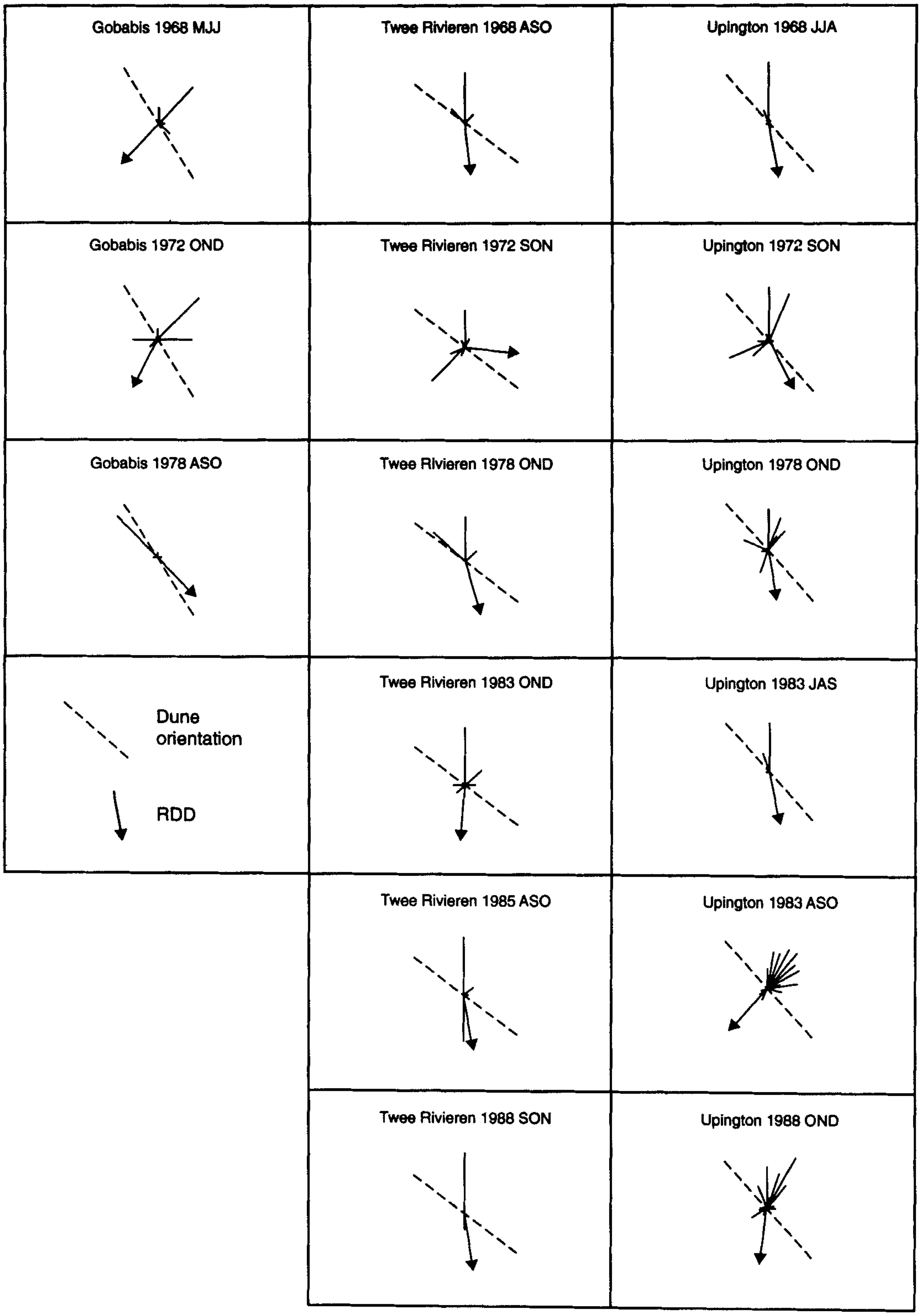


Figure 10. RDD for three-month DP maxima and average dune orientation for Gobabis, Twee Rivieren and Upington

(1995), it can be observed here that a strong regional trend in increasing dune pattern complexity runs from the northwest to southeast in the dunefield, with an additional, less-marked, southwest–northeast trend running across the southern half of the dunefield (Figure 3). If the dunefield developed under present-day wind regimes or at a past time when regimes were the same, it might be expected that levels of simplicity and complexity in dune pattern and potential sand-transporting wind regimes would broadly coincide. Therefore, dunes of classes 1 and 2 (Figure 2) would be expected where RDP/DP is highest (i.e. representing lowest directional variability: Table I) and dune patterns of greater complexity where RDP/DP values are lower (representing greater directional variability).

Values in Figure 9 demonstrate that RDP/DP values over the whole dunefield during the study years fell in the 0·2–0·8 range, embracing all three variability categories of Fryberger (1979: Tables I and II). In the south of the dunefield, at Upington, RDP/DP values in each of the six years are amongst the highest, usually in the intermediate variability category. Class 1 (parallel to sub-parallel, discontinuous) dunes dominate this part of the dunefield. Observation of case studies from other desert dunefields by Breed *et al.* (1979) indicates that such a relationship between sand-transporting regimes and dune patterns may be compatible in terms of the development of the dune pattern. Elsewhere in the dunefield the situation is inconclusive. It can be noted however that at Gobabis, at the north of the dunefield where dunes are straightest and most continuous, and at Keetmanshoop, in the vicinity of which dunes are also straight and continuous, the most consistently low (but not absolute lowest) RDP/DP values are recorded. If these parallel dunes were being formed today, less directional variability of the wind regime might be expected.

CONCLUDING REMARKS

The investigation outlined above represents a first attempt to analyse winds at the scale of a whole dunefield at other than an averaged, simplistic level. The analysis has significant implications for attempting to relate dunefield aeolian activity or dune activity to studies either based on a single year's data or averaged data. However, these implications need to be viewed in the light of several limitations that affect the data set. First, this study required meteorological data as an input to the modified 'Fryberger Method' of analysis. These data were obtained from national meteorological offices, as they represented the only source of relatively long data sets covering the whole dunefield. Two principal problems were encountered with the data, notably that major gaps existed in data for individual stations and the weather station facilities for wind data collection did not always follow WMO standard recommendations regarding the height and location of anemometers. It is not possible to determine fully the impact of these factors on the quality of data, but they must be borne in mind when conclusions are drawn.

From the analyses presented, the following points can be noted about the nature of the modern potential sand-transporting environment in the dunefield of the southwestern Kalahari Desert.

1. From detailed at-a-dune studies of dune surface activity, conducted in the Kalahari in 1992 (Wiggs *et al.*, 1995; 1996) it was noted that the available wind energy was a factor limiting sand transport on all but the crests of dunes. Ash and Wasson (1983) also proposed a similar role for insufficient wind energy in the Simpson Desert. By analysing data from place to place and year to year in the Kalahari, it has been shown that while periods of low wind energy do occur, there are other times, notably during the 1980s, when high potential sand transport energy environments occurred. Inter-annual variability therefore appears high. This indicates that (a) the findings of short-term field-based studies of dunefield aeolian processes have to be set in the context of the regional wind environment prevailing at the time of the study and (b) that using temporal mean wind data to characterize dunefield wind environments may be inadequate. The length of the data set precludes a firm consideration of whether the Kalahari dune environment today is predominantly a low or high energy one. However, it cannot be automatically assumed that low energy conditions dominate, as has occurred in other studies. There is clear evidence to demonstrate that higher energy conditions do occur at the decade scale.
2. The lack of consistency in the temporal component of the Kalahari wind environment extends to intra-annual variability in the timing of greatest potential sand movement. Although this paper has focused on

the wind environment, both inter- and intra-annual components of its variability affect the overall issue of sand transport. For a fuller investigation of dunefield activity, it is necessary to consider more fully these scales of variability and how they interact with variability in other climatic parameters, notably rainfall, that may influence sediment transport (Thomas 1991; Livingstone and Thomas, 1993).

3. It is not known whether the variability in the potential sand-transporting environment identified in this study is a characteristic of the Kalahari alone, or whether it is applicable to other dunefields too. In this respect, Livingstone and Thomas (1993) have argued that linear dune activity may be episodic at a number of scales. This paper indicates that this episodicity may not only be in terms of variations in vegetation cover on partially vegetated dunes (e.g. Wiggs *et al.*, 1994), but also in terms of wind energy.
4. Attempts were made to compare the orientation and pattern of dunes within the Kalahari dunefield with differences in RDP and RDP/DP, which has implications for both the regional environments of linear dune development and whether or not the dunes developed under a circulation regime comparable to that of today. The comments concerning the general variability within the wind environment made above are also applicable to this aspect of the study, preventing clear conclusions being drawn. However, in the northern and western areas of the dunefield that possess straight continuous dune ridges, directional variability during the period covered by the data may exceed that under which such dunes could be expected to form. Wind directional conditions in the southern part of the dunefield, where discontinuous but predominantly straight ridges occur, may be in agreement with dune orientations.
5. During the period of analysis, there was a lack of coincidence in mean dune orientation and the RDD for the blocks of months with the greatest DPs. This may support the view that the dunes are out of equilibrium with present environmental conditions, but takes no account of the effect of dunes in modifying air-flow direction (cf. Tsoar, 1978).

These statements primarily refer to dune development, whereas the activity of a dune system can be considered in terms of dune initiation or development, dune form maintenance and surface sand activity (Livingstone and Thomas, 1993). It may well be the case that parallelism between dune orientations and RDD, or the relations between the complexity of the dune pattern and the complexity of the wind regime, are not prerequisites for surface aeolian activity to occur or for a dunefield to be considered in equilibrium with contemporary environmental conditions. This is because dune activity can be considered to occur in a number of different states (Livingstone and Thomas, 1993), and because it may be important to distinguish between dune-forming winds, which would affect pattern initiation, and sand-moving winds in an existing dunefield. The dune patterns observed today may represent a modification of pre-existing dune patterns and bear some relation to both the formative and modifying wind regimes. Sand transport may also be localized across a dune body in response to the total range of influencing factors, especially in a partially vegetated environment (Wiggs *et al.*, in press a), while the intrusion of a dune into the atmospheric boundary layer may have an influence both on local wind velocities and wind-flow direction across the dune (Tsoar, 1985).

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